Light colored scalars and the up quarks phenomenology

Svjetlana Fajfer
Physics Department, University of Ljubljana and Institute J. Stefan, Ljubljana, Slovenia

Univerza v Ljubljani

RTN network FLAVIAnet

July 5-7 2010, Capri, Italy

Outline

1. Phenomenological constraints on new physics in the up-quark sector:

- Forward-backward asymmetry in $t\bar{t}$ production;
- Constraints from single top production at Tevatron;
- D mesons system;

2. SU(5) GUT with 45 Higgs representation and limits on proton decay;

3. Constraints on the Yukawa couplings in the up-quark sector;

3. Search strategies for the relatively light colored scalar

Based on:
Ilja Dorsner, Svjetlana Fajfer, Jernej F. Kamenik, Nejc Kosnik:Phys.Rev.D81:055009,2010.
Phys.Lett.B682:67-73,2009, S.F. and N. Kosnik, Phys.Rev.D79:017502,2009.
I.D., S.F., JFK, N.K., in preparation;

Forward backward asymmetry in the top pair production at Tevatron

- top quark is the heaviest fundamental fermion;

- top quark mass is important for constraints of the Higgs boson mass and the electroweak symmetry breaking ;

- production of top quarks in pairs offers an important probe of strong interactions;

Discovery: Fermilab Tevatron collider (1996)

$$\boxed{q\bar{q} \longrightarrow t\bar{t} \;\; \& \;\; gg \longrightarrow t\bar{t}}$$

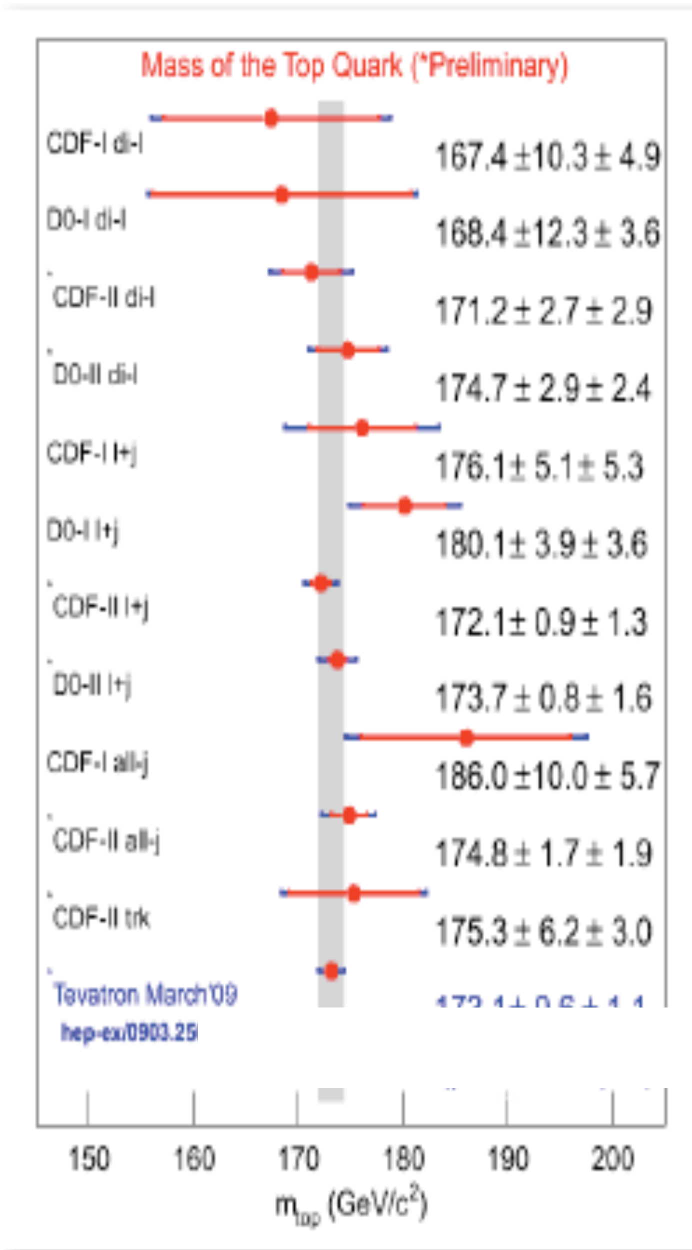
$$Q = \frac{2}{3}$$

$$m_t = 173.1 \pm 1.3 \;\; GeV$$

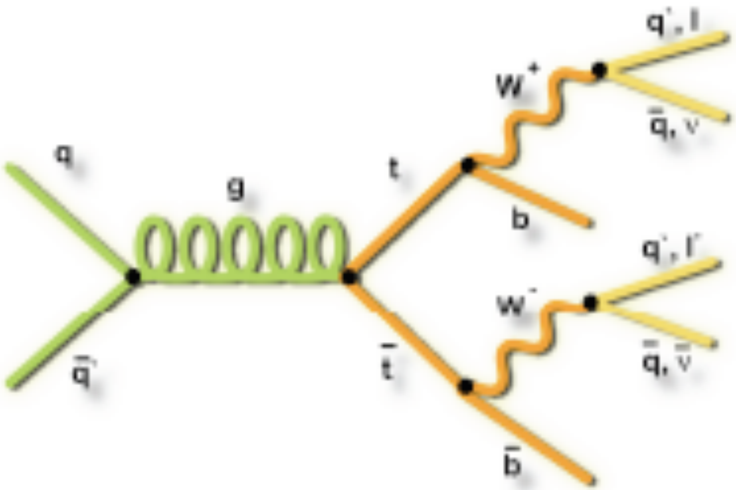
Tevatron results:

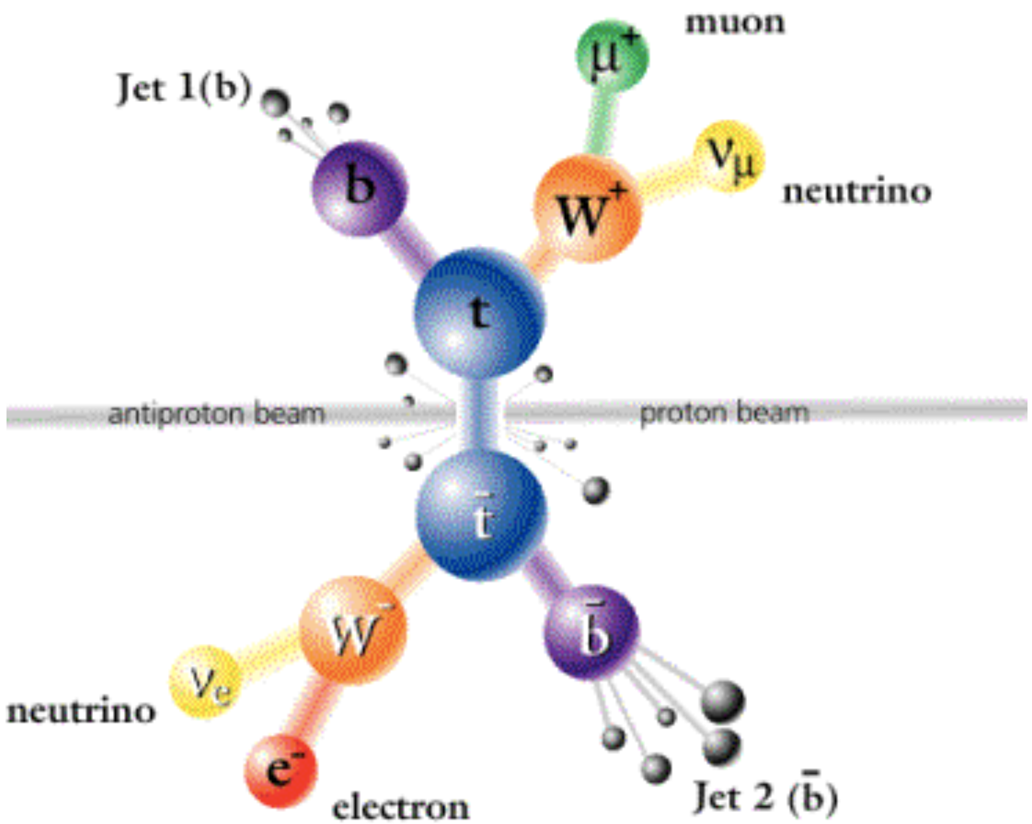
The precise measurement of the top quark mass : how one can gain from the electroweak precision observables by improving the experimental precision.

Production:
- double top production;
- single top production.

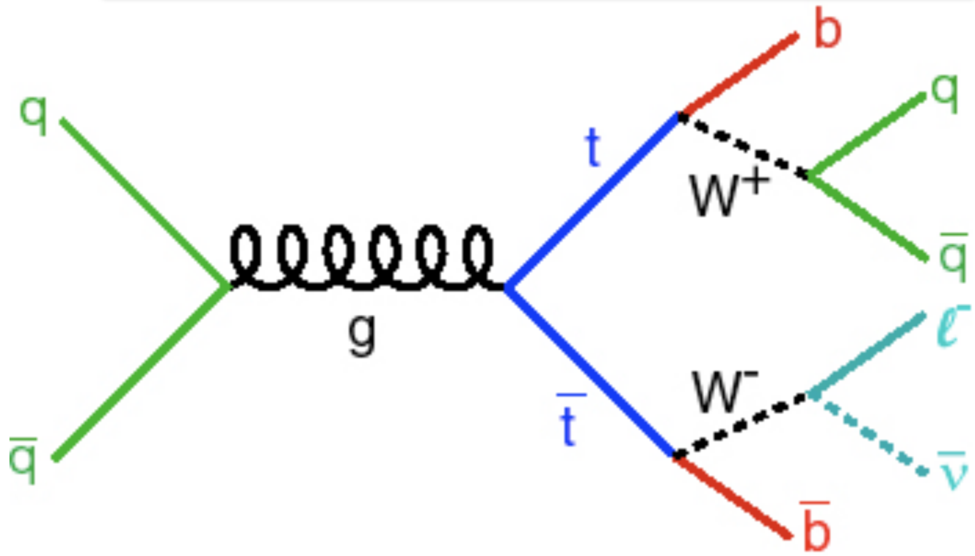


Double top production at Tevatron



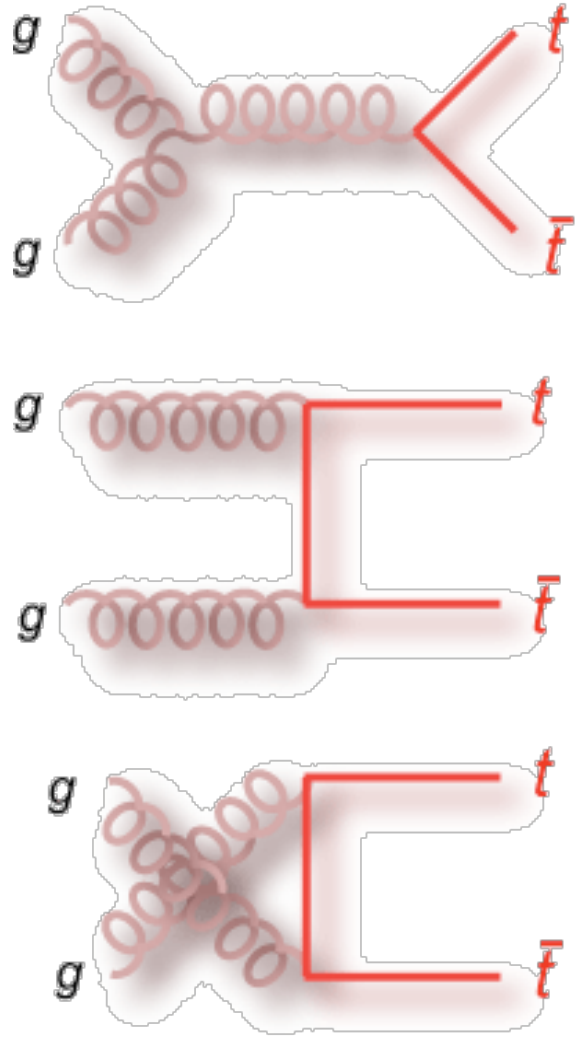


At Tevatron dominant production mechanism



~85%

At LHC is the opposite situation: gg dominant !



~ 15 %

Recent experimental results in double top production

- Forward-backward asymmetry:

$$A_{FB} = 0.193 \pm 0.065(stat)] \pm 0.024(syst)$$

(CDF, consistent with previous CDF and D0 results)

- Standard model predicts: $A_{FB} = 0.05 \pm 0.08$ (2σ effect)

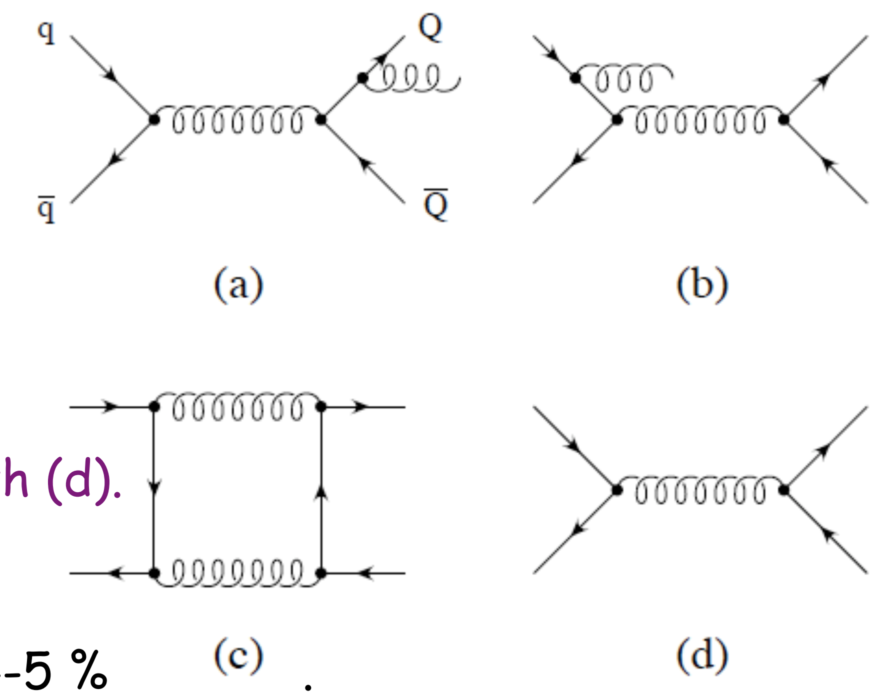
- However, the production cross section agrees with Standard Model prediction.

Difficult to explain within SM!

New Physics?

Standard Model and FBA

-Kühn and Rodrigo, 1998

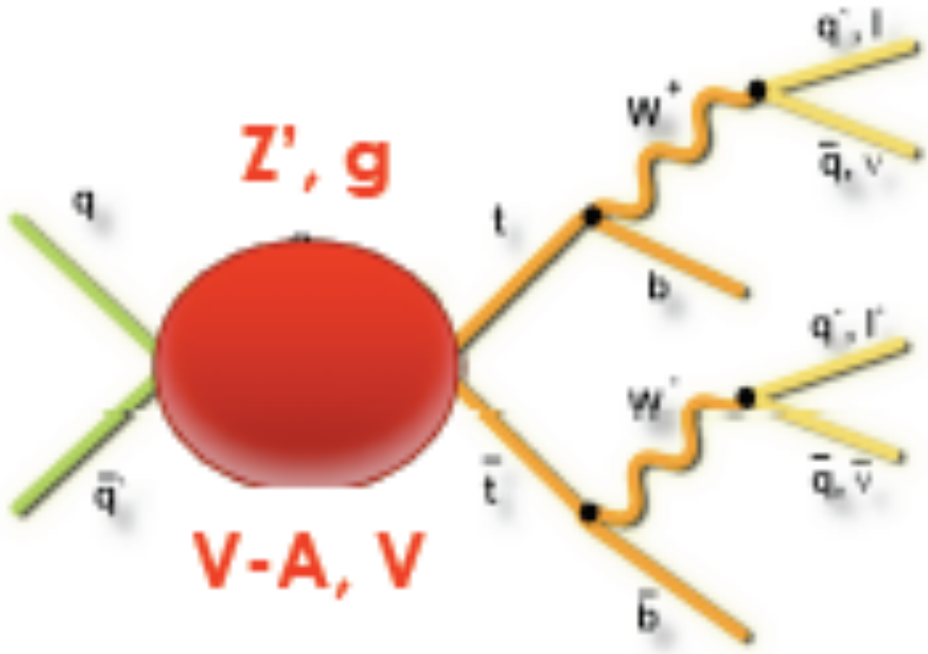


The origin of FB asymmetry in QCD:
interference of (a) with (b) and (c) with (d).

The effect should be of the order 4-5 %

- Ahrens et al, 2010 NLO+NNLL; FB asymmetry excess cannot be explained

- Boughzel and Petriello, 2010, NLO in top pair production +color octet scalars;



Many attempts to explain it:

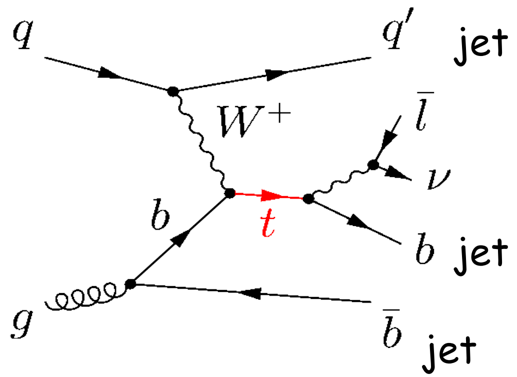
- Z', $M_{Z'} \approx 160\,\mathrm{GeV}$ Jung et al, 2009;

- Kaluza – Klein gluon excitation with the mass of around 3 TeV, Djuadi et al. 2009;

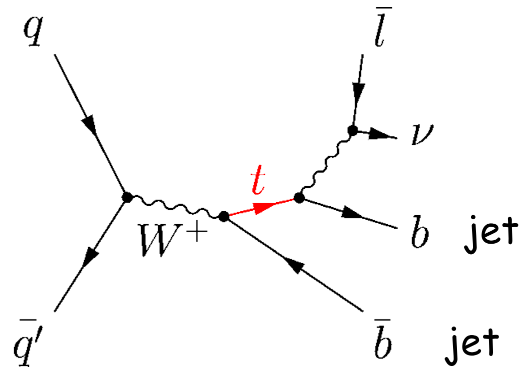
- Axigluons (mass in the range 0.6 - 1.4 TeV) Ferreira and Rodrigo, 2009, 1007.0260 Chivikula et al. showed that Bd oscillations exclude this model explaining FBA)

Single top production at Tevatron

First observation of single top event in 2009 (CDF and D0);



t channel



s channel

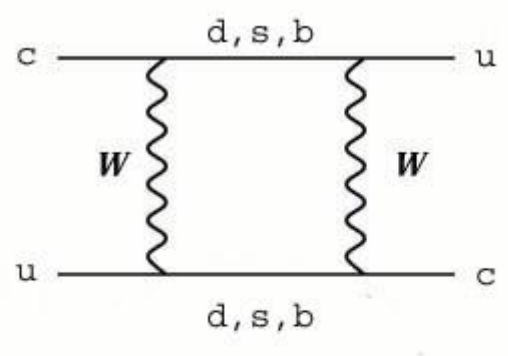
Single top is produced by the weak interaction
(contrary to double top anti- top which are produced by the strong interaction)

Remaining up quarks: c and u

Most restrictive for FCNC : $D^0 - \bar{D}^0$

The neutral D meson system is the only one created out of the up-type quarks.

Standard model



- intermediate down-type quarks
- due to CKM contribution of b – quark negligible;
- in the SU(3) limit 0;
- long distance contributions important;

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle, \qquad |D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$$

Experiments are measuring

$$m \equiv \frac{m_1 + m_2}{2}, \qquad \Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2},$$

$$x \equiv \frac{m_2 - m_1}{\Gamma}, \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}.$$

Gedalia, Grossman, Nir, Peres, 2009;
Golowich, Petrov, Pakvasa, 2007, 2009;
Bigi, Buras et al., 2009

If there is no observation of CP violation in D mixing this is very useful constraint on new physics.

$$A_f = \langle f|\mathcal{H}|D^0\rangle, \qquad \bar{A}_f = \langle f|\mathcal{H}|\bar{D}^0\rangle$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

$$\lambda^{-1}_{K^+\pi^-} = r_d \left|\frac{p}{q}\right| e^{-i(\delta_{K\pi}+\phi)},$$
$$\lambda_{K^-\pi^+} = r_d \left|\frac{q}{p}\right| e^{-i(\delta_{K\pi}-\phi)},$$
$$\lambda_{K^+K^-} = -\left|\frac{q}{p}\right| e^{i\phi},$$

Recent update by HFAG (FPCP 2010):

$$x = (0.59 \pm 0.20)\,\% \qquad |q/p| = 0.98^{+0.15}_{-0.14},$$
$$y = (0.81 \pm 0.13)\,\% \qquad \phi = -0.051^{+0.112}_{-0.115}.$$

It means that
- width and mass splitting are at a level close to 1%;
- CP violation is small.

Models of new physics in $\Delta C = 2$

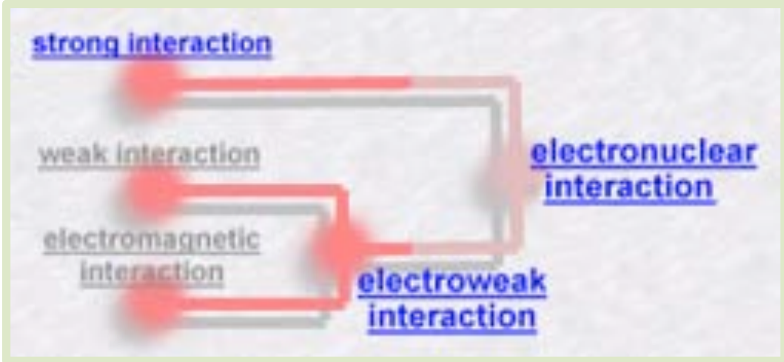
- additional gauge bosons; → left-right model ; horizontal symmetries etc.;
- additional scalars; → two-Higgs doublet models, leptoquarks;
- additional fermions; → e.g. 4^{th} generation, vector-like quarks; mirror fermions;
- additional dimensions; → UED, warped ED;
- additional symmetries; → SUSY: MSSM, split susy;

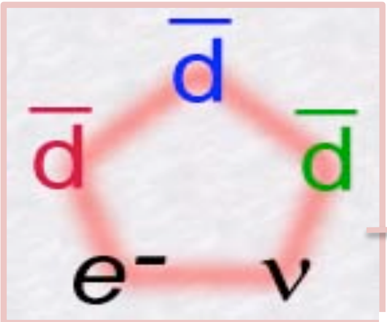
GUT approaches

Georgi-Glashow (1974) proposed

$$SU(5)$$

$$\overbrace{SU(3) \times SU(2) \times U(1)}$$

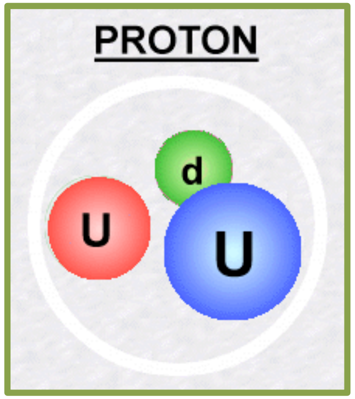




Matter fields are in representation

5 and $\overline{10}$

Unifications of the strong, weak and electromagnetic interactions occurs at the scale 10^{16} GeV.



Proton might decay:
Current experimental limit

$$\tau_p > 10^{33} \text{ years}$$

SU(5) embedding

Matter fields :

$$\mathbf{10_i}(= (\mathbf{1},\mathbf{1},\mathbf{1})_\mathbf{i} \oplus (\overline{\mathbf{3}},\mathbf{1},-\mathbf{2}/\mathbf{3})_\mathbf{i} \oplus (\mathbf{3},\mathbf{2},\mathbf{1}/\mathbf{6})_\mathbf{i} = (\mathbf{e_i^C},\mathbf{u_i^C},\mathbf{Q_i}))$$
$$\overline{\mathbf{5}}_i(= (\mathbf{1},\mathbf{2},-\mathbf{1}/\mathbf{2})_\mathbf{i} \oplus (\overline{\mathbf{3}},\mathbf{1},\mathbf{1}/\mathbf{3})_\mathbf{i} = (\mathbf{L_i},\mathbf{d_i^C}))$$
where $Q_i = (u_i \quad d_i)^T$ and $L_i = (\nu_i \quad e_i)^T$.

up quark (down quark and charged lepton) masses originate from the contraction of

$\mathbf{10_i}$ and $\mathbf{10_j}$ ($\overline{\mathbf{5}}_j$) with 5- and/or 45-dimensional Higgs representation.
$\mathbf{10}\times\mathbf{10} = \overline{\mathbf{5}} \oplus \overline{\mathbf{45}} \oplus \overline{\mathbf{50}}$ and $\mathbf{10}\times\overline{\mathbf{5}} = \mathbf{5}\oplus\mathbf{45}$.

most general renormalizable set of Yukawa coupling contractions with $\mathbf{5_H}$ and $\mathbf{45_H}$ is

$$\begin{aligned} V &= Y_{5^*}^{ij}\mathbf{10}_i^{\alpha\beta}\overline{\mathbf{5}}_{\alpha j}\mathbf{5}^*_{H\beta} + Y_5^{ij}\epsilon_{\alpha\beta\gamma\delta\epsilon}\mathbf{10}_i^{\alpha\beta}\mathbf{10}_j^{\gamma\delta}\mathbf{5}_H^\epsilon \\ &+ Y_{45^*}^{ij}\mathbf{10}_i^{\alpha\beta}\overline{\mathbf{5}}_{\delta j}\mathbf{45}^{*\,\delta}_{H\alpha\beta} + Y_{45}^{ij}\epsilon_{\alpha\beta\gamma\delta\epsilon}\mathbf{10}_i^{\alpha\beta}\mathbf{10}_j^{\zeta\gamma}\mathbf{45}_{H\zeta}^{\delta\epsilon}, \end{aligned}$$

Inclusion of 45 Higgs representation

$$\boxed{M_E^T = M_D}$$

In GUT there is a problem with masses of charged fermions at the GUT scale

$$\boxed{m_\tau / m_b = m_\mu / m_s = m_e / m_d}$$

Solutions:
- extra vectorlike fermions;
- higher dimensional operators(45);

Higgs in 45 modifies:

$$\boxed{M_E^T = -3 M_D}$$

Both are needed: Higgses in 5 and 45!

45 representation should be part of any simple renormalizable SU(5) GUT without SUSY.

In 45 Higgs representation there are many new scalars

"genuine" leptoquarks

$$\mathbf{45_H} = (\boldsymbol{\Delta_1}, \boldsymbol{\Delta_2}, \boldsymbol{\Delta_3}, \boldsymbol{\Delta_4}, \boldsymbol{\Delta_5}, \boldsymbol{\Delta_6}, \boldsymbol{\Delta_7}) = \\ (\mathbf{8}, \mathbf{2}, \mathbf{1/2}) \oplus (\mathbf{\overline{6}}, \mathbf{1}, \mathbf{-1/3}) \oplus (\mathbf{3}, \mathbf{3}, \mathbf{-1/3}) \oplus (\mathbf{\overline{3}}, \mathbf{2}, \mathbf{-7/6}) \oplus (\mathbf{3}, \mathbf{1}, \mathbf{-1/3}) \oplus (\mathbf{\overline{3}}, \mathbf{1}, \mathbf{4/3}) \oplus \\ (\mathbf{1}, \mathbf{2}, \mathbf{1/2})$$

colored scalars

- "genuine" leptoquark interacts always with one lepton and one quark;
- colored scalars might interact with two quarks only

$$\boxed{\Delta_6 = (\bar{3}, 1, 4/3)}$$

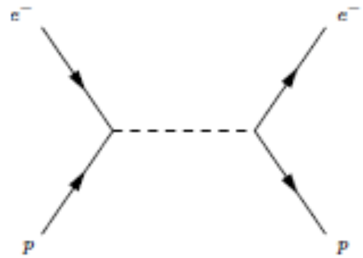
role of leptoquark with down-like quarks

role of diquarks with the up-like quarks

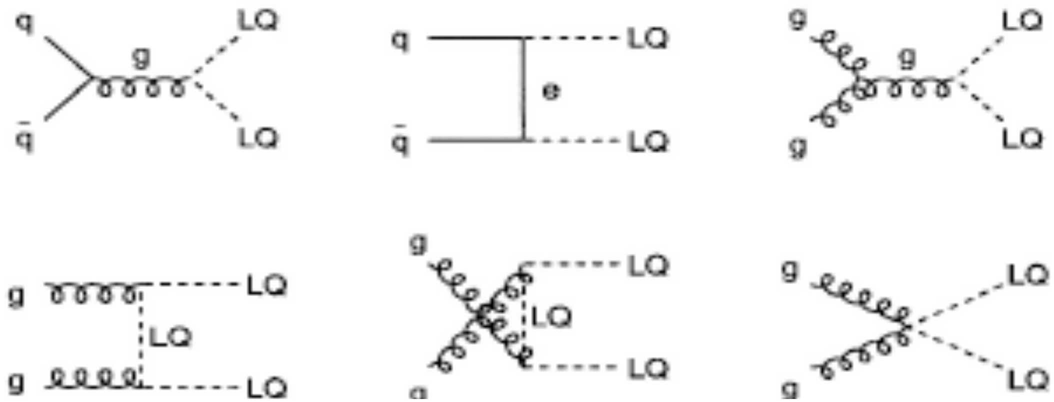
Leptoquarks

- arise naturally in unification theories, Pati-Salam, R-parity violating SUSY, extended technicolor, compositeness models;
- Experimentally they have been searched directly:

Single production at $e^{\pm}p \to e^{\pm}p$ experiments (HERA, ZEUS)
$\Rightarrow$ Constraints in the coupling-mass plane

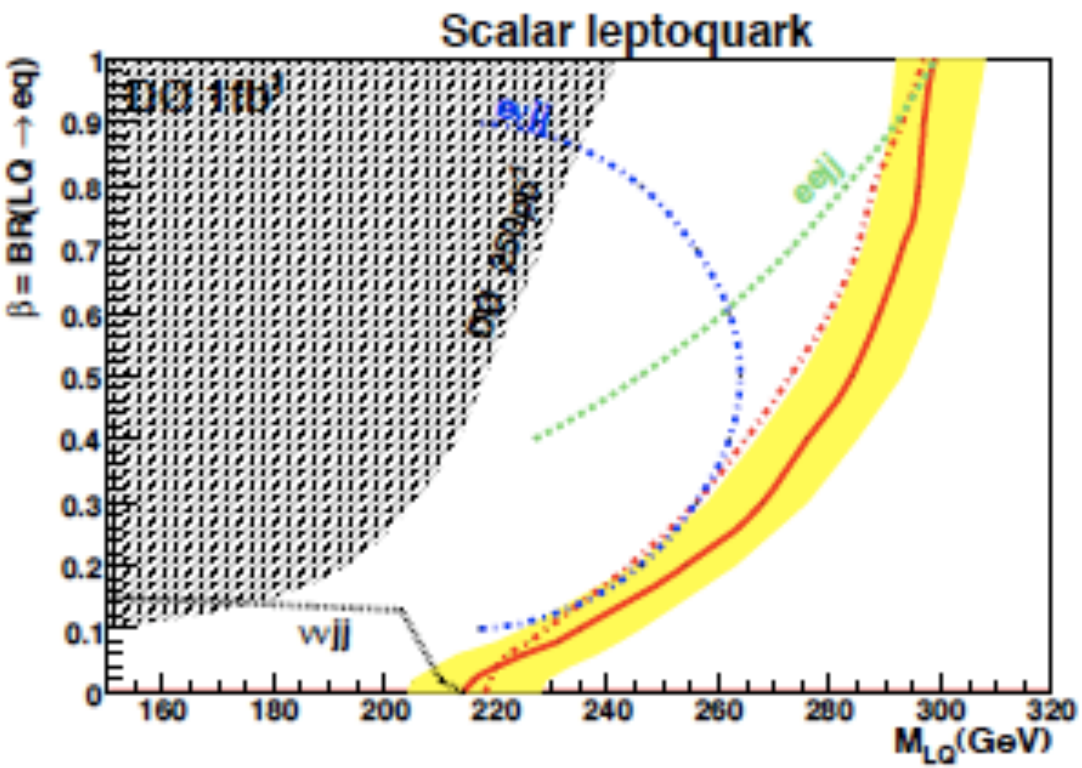


- Pair production in hadron colliders



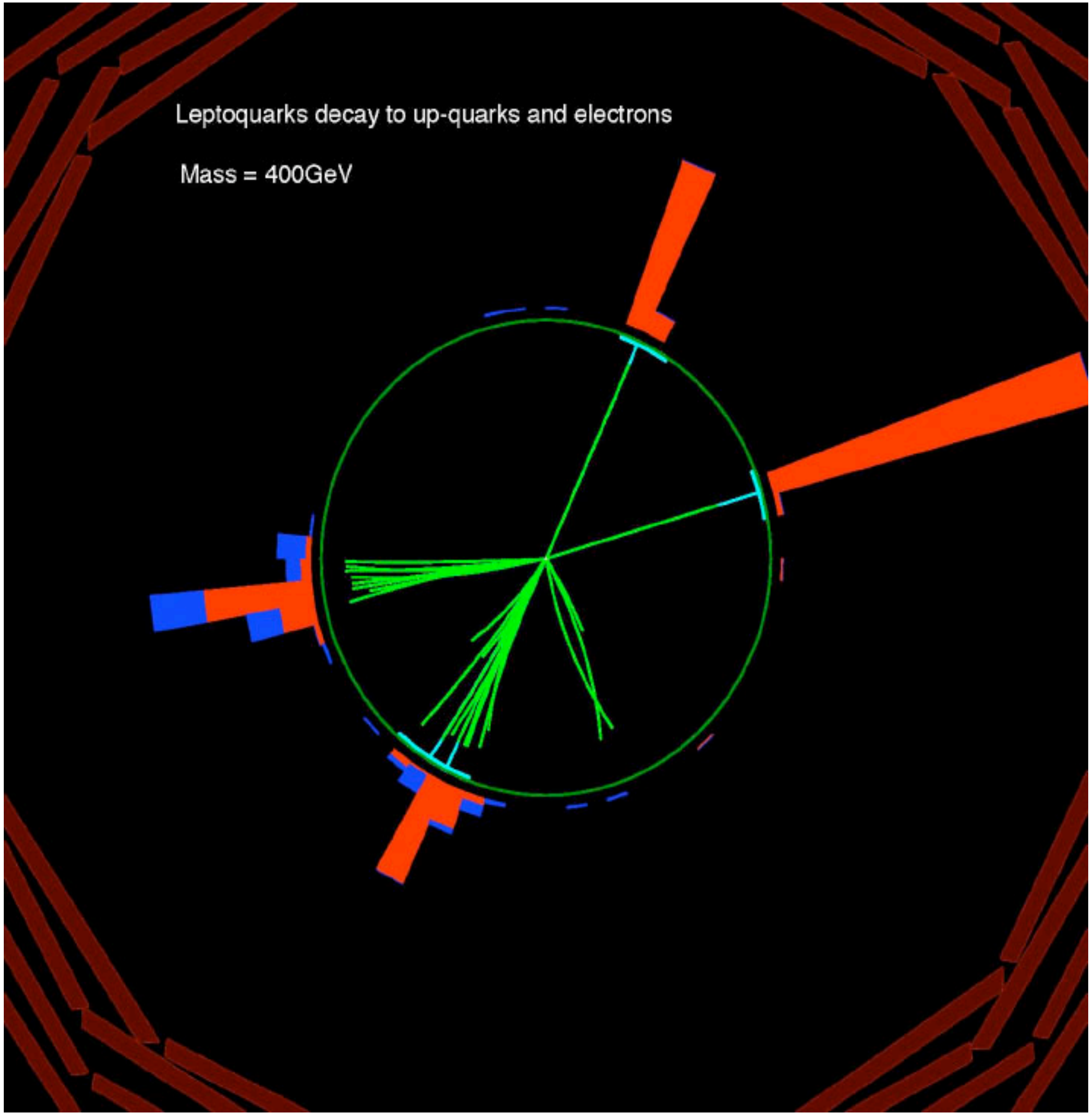
★ False indication for on-shell production in HERA e p sscattering (1997)

★ Lower bound on mass from D0, CDF in the range 230 – 250 GeV



arXiv: 0907.1048

(first generation)



Leptoquarks decay to up-quarks and electrons
Mass = 400GeV

Is unification possible with the light colored scalars ?

At one loop level, two equations should be satisfied:

Unification conditions:

$$\boxed{\begin{aligned} \frac{B_{23}}{B_{12}} &= \frac{5}{8}\frac{\sin^2\theta_W - \alpha/\alpha_3}{3/8 - \sin^2\theta_W} = 0.716 \pm 0.005, \\ B_{12} &= \frac{16\pi}{5\alpha}(3/8 - \sin^2\theta_W) = 184.9 \pm 0.2. \end{aligned}}$$

$$B_{ij} = B_i - B_j$$

$$\boxed{B_i = \sum_I b_{iI} \ln M_{GUT}/m_I}$$

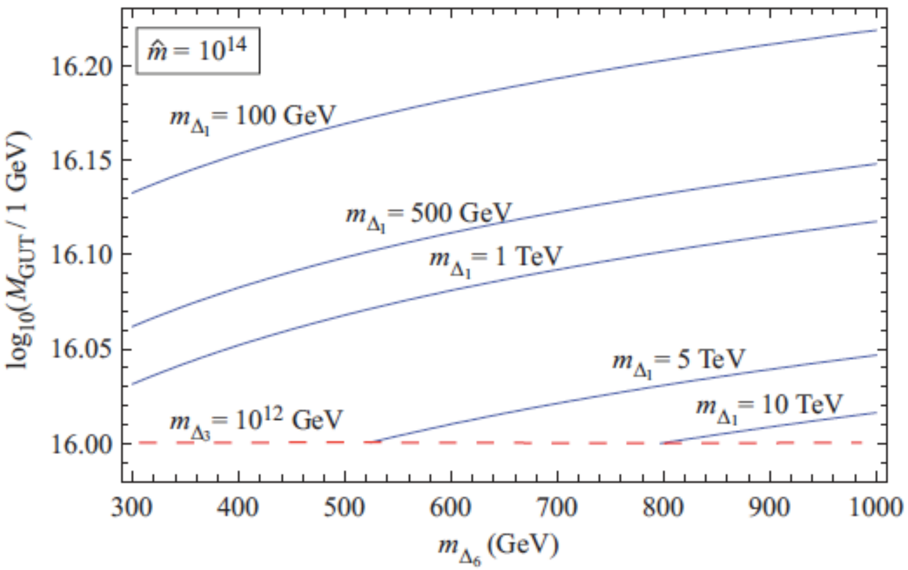
Experimental constraints:

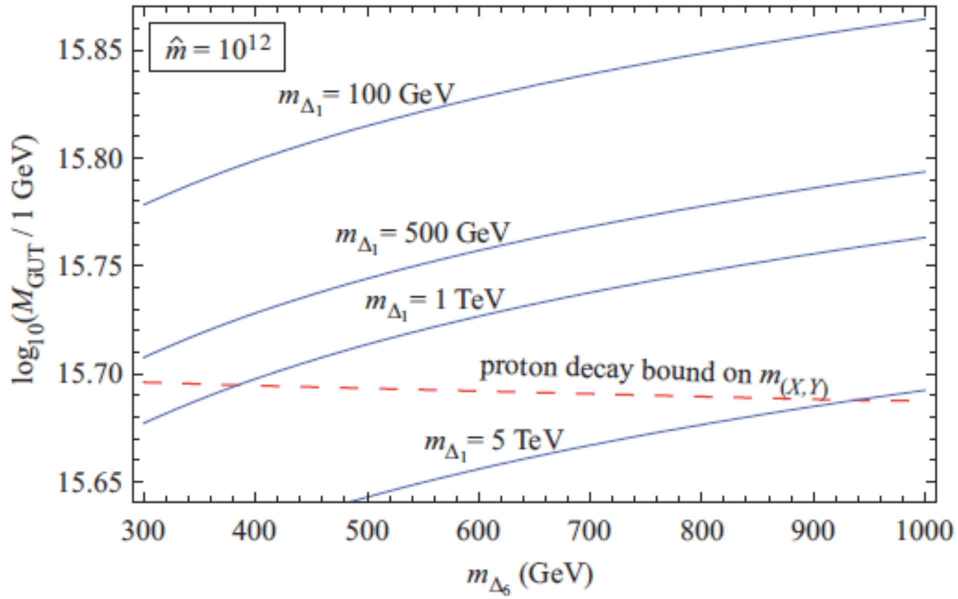
$$(M_Z \le m_I \le M_{GUT})$$

$$\alpha_3 = 0.1176 \pm 0.0020,\ \alpha^{-1} = 127.906 \pm 0.019$$

$$\sin^2\theta_W = 0.23122 \pm 0.00015$$

experimental result on proton lifetime: $\boxed{\tau(p \to \pi^0 e^+) > 8.2 \times 10^{33}}$





Unification is possible if Δ_6 and Δ_1 are both relatively light.
We varied all relevant masses from 100 GeV to GUT scale .

Comment: If the partial lifetime of proton $p \to \pi^0 e^+$ is improved by factor 6 then $300\mathrm{GeV} \le m_{\Delta_6} \le 1\mathrm{TeV}$ will be excluded.

Δ_1 and Δ_6

Within SU(5) GUT model we have to consider both states:

$$45 = (\Delta_1, \Delta_2, \underbrace{\Delta_3, \Delta_4, \Delta_5}, \Delta_6, \Delta_7)$$

Experimental results from K and D phenomenology almost exclude presence of these light state at low energies
Dorsner, S.F, N. Kosnik, J.F. Kamenik, (2009)

Δ_1: $(8, 2, 1/2)$

Δ_6: $(\overline{3}, 1, 4/3)$

$$\Delta_1^a = \begin{bmatrix} \Delta_1^{a,+} \\ \Delta_1^{a,0} \end{bmatrix}$$

$a = 1, ..., 8$

Δ_6:

- 3 colored states
- $(1+\gamma_5)$ in the weak interactions
- electric charge 4/3

Proton decay and colored triplet scalar

Δ_6 innocuous for proton decay at the tree level ;
(dangerous mixing with Higgs doublet from 5 avoided due to scalars 24)

Neutrino masses:

In addition to 5, 45, 24 scalars one 15 scalars needed for the neutrino masses type II seesaw. Problem: GUT scale to low being around $10^{13}\,\mathrm{GeV}$.

Our scenario: neutrino masses generated by seesaw combination type I and type III with the new fermions in adjoint representation (Bajc and Senjanović ,2008, Dorsner and Mocinou , 2009), instead of representation 15.

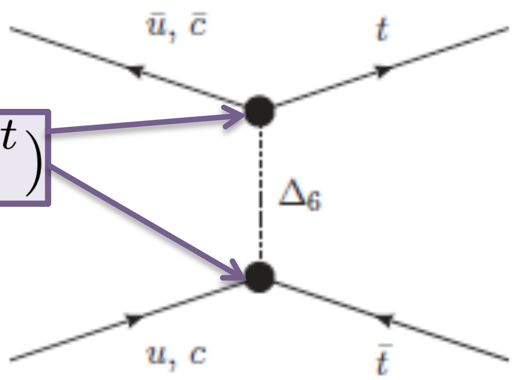
The $t\bar{t}$ production cross-section and the forward-backward asymmetry and colored scalars

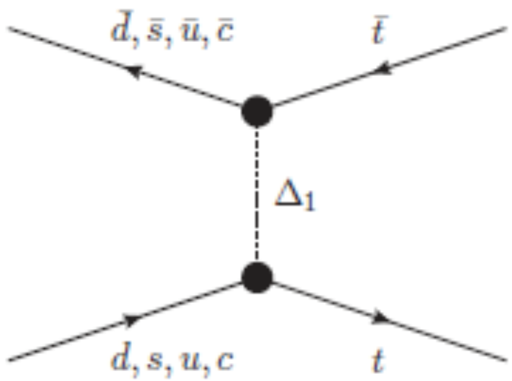
Standard Model LO production

Our assumption SM + NP

Important interference of NP and SM

$$\boxed{g_6^{qt} = 2\sqrt{2}(Y_2^{qt} - Y_2^{qt})}$$





$$\boxed{\hat{t} = (p_u - p_t)^2,\ \hat{u} = (p_{\bar{u}} - p_t)^2}$$

Using partonic distribution functions

$$\boxed{\frac{d\sigma(s)}{dt} = \sum_{p,p'=q,g} \int_{x_0}^{1} dx_1 \int_{x_0}^{1} dx_2 x_1 x_2 \frac{d\sigma^{pp'}(\hat{s})}{d\hat{t}} f_p(x_1) f_{p'}(x_2)}$$

$$\frac{d\sigma(s)}{d\theta} = \frac{s\beta_t}{2} \frac{d\sigma(s)}{dt(\theta)}$$

we have to sum over all quark and gluon contribution

the polar angle of the $t\bar{t}$ production

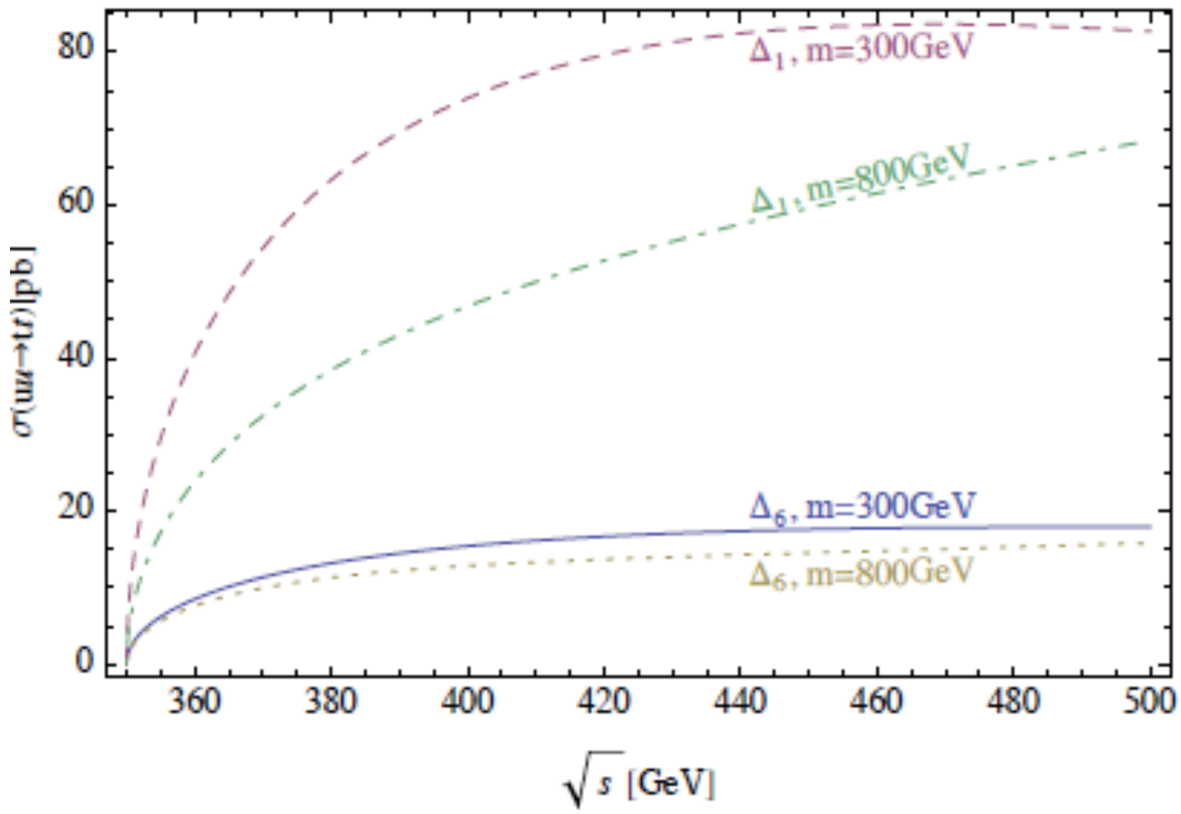
Simultaneous fit to the integrated cross section and AFB

$$A_{FB}^{t\bar{t}}(s) = \frac{\int_0^1 d\theta[d\sigma(s)/d\theta] - \int_{-1}^0 d\theta[d\sigma(s)/d\theta]}{\sigma_{t\bar{t}}(s)}$$

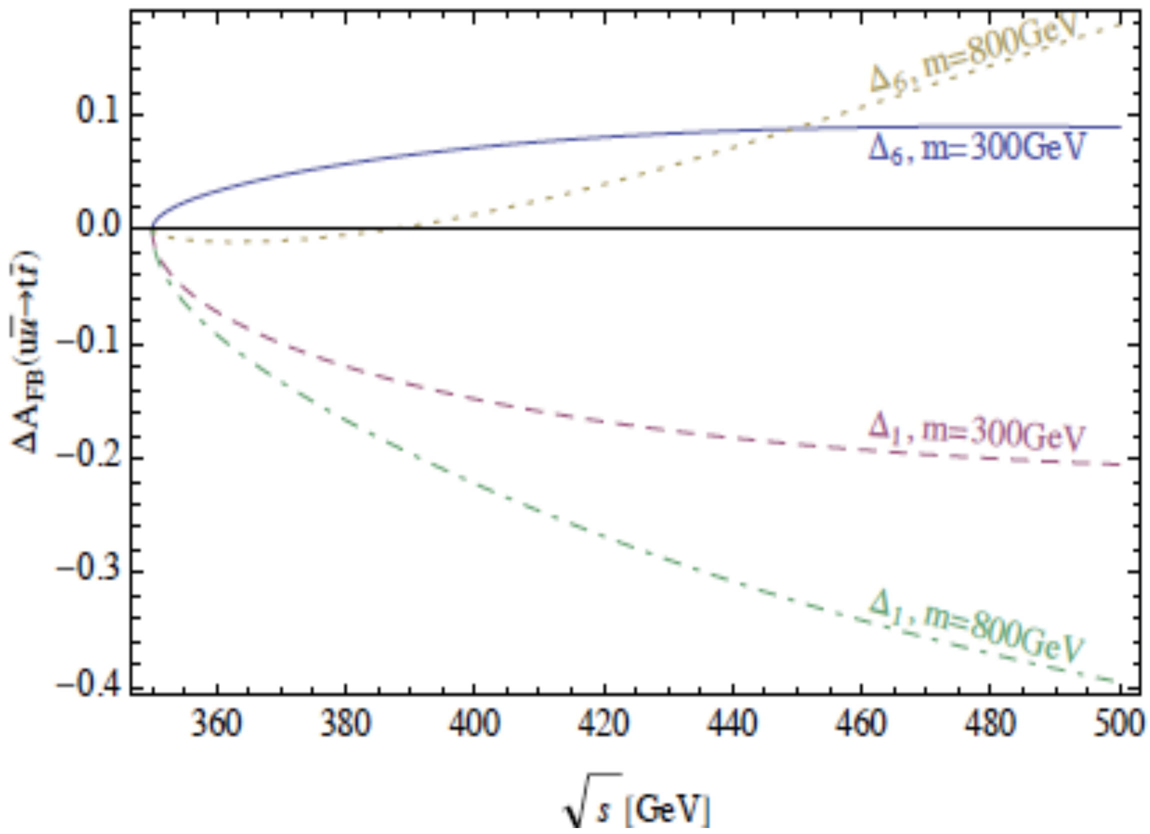
$$\sigma_{t\bar{t}}(s) = \int_{-1}^{1} d\theta[d\sigma(s)/d\theta] \, .$$

$$\sigma_{t\bar{t}}^{exp} = 7.0 \pm 0.6 \text{ pb}$$

$$A_{FB}^{exp} - A_{FB}^{SM} = (14.2 \pm 6.9)\%$$

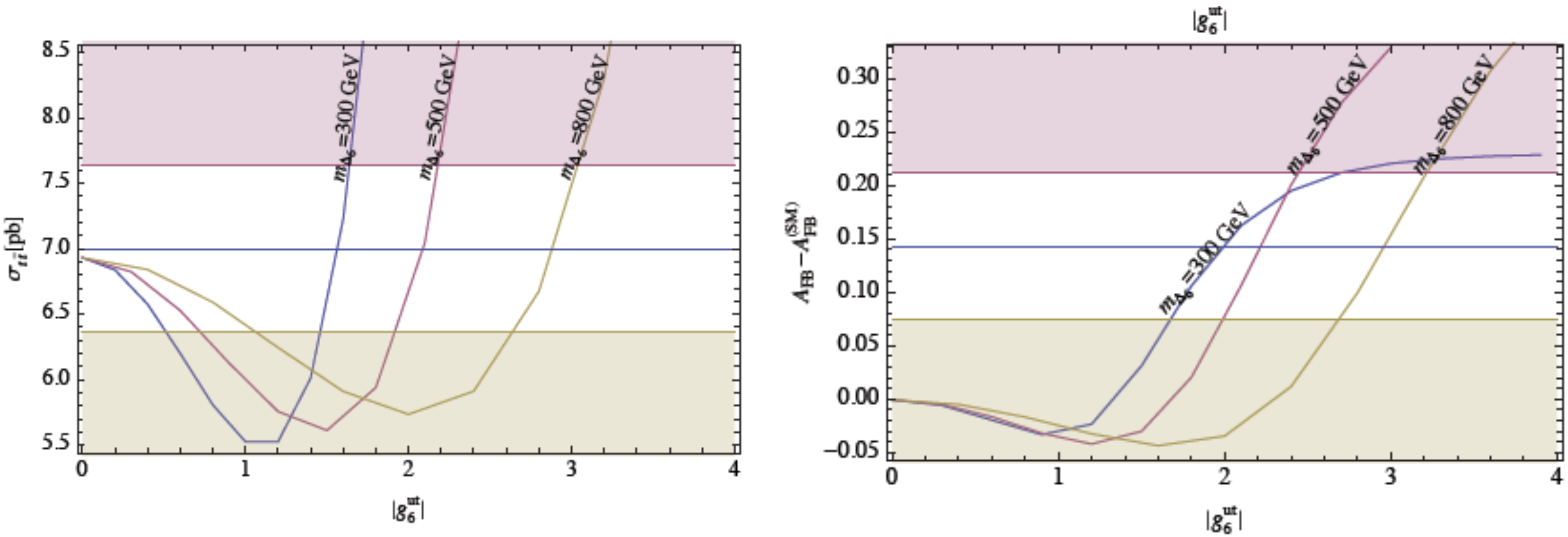


The colored octet scalars at the partonic level cannot induce large positive AFB. The contributions of Δ_1 interfere constructively with the SM amplitude resulting in big enhancement in the cross section.



The Δ_6 gives moderate increase in the cross section and gives positive AFB, while AFB is negative for Δ_1.

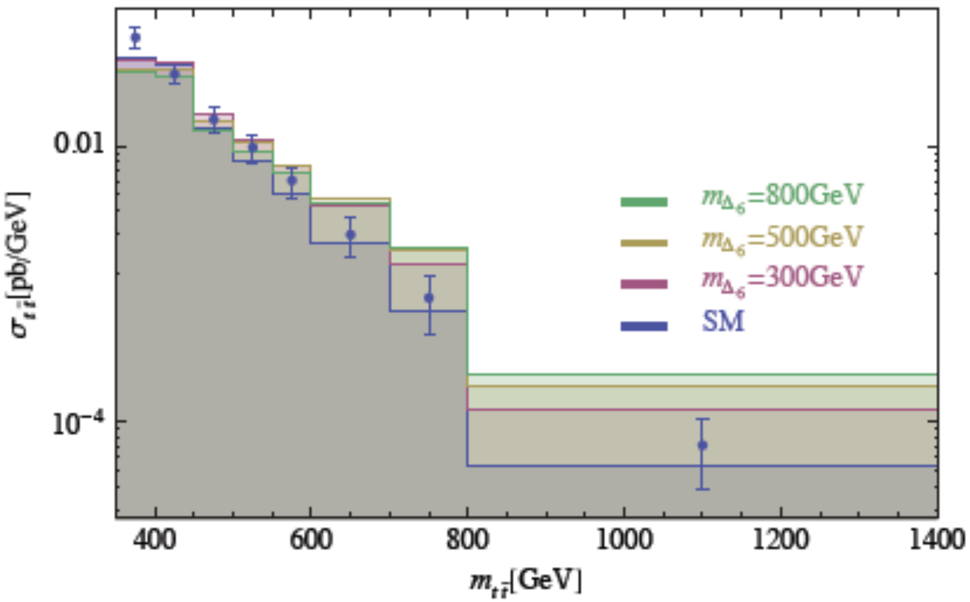
The contribution of Δ_1 should be suppressed compared to the one coming from Δ_6.

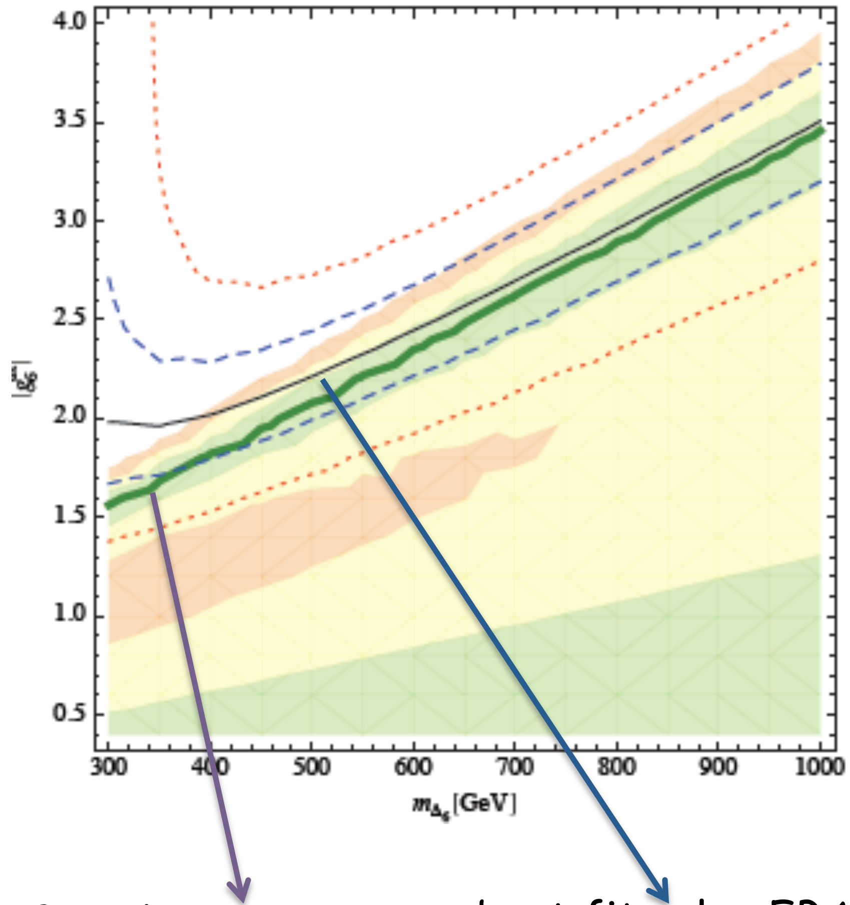


Examples of the hadronic $t\bar{t}$ cross-section and the forward-backward asymmetry at Tevatron including Δ_6. The shaded regions are outside one sigma experimental bound. Our study implies:

$$m_{\Delta_6} \geq 300\,\mathrm{GeV}$$

best fit value for $\boxed{g_{13}^6 = 0.9(2) + 2.5(4)\dfrac{m_{\Delta_6}}{1\ TeV}}$

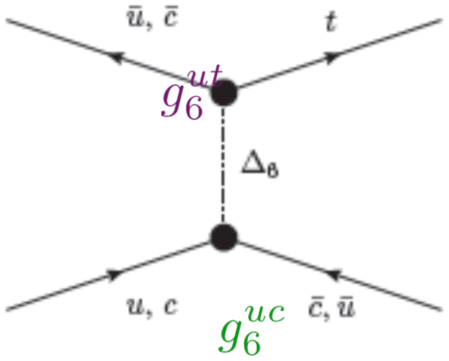




best fit value- σ best fit value FBA

The contribution of colored singlet to the $m_{t\bar{t}}$ invariant mass spectrum in $t\bar{t}$ production at Tevatron (left). Constraints on the parameter space of Δ_6.
Green, yellow and orange denote 68%, 95%, 99% confidence level regions in the production cross section.
FBA are bounded by blue dashed (68 % C.L.) red dotted (95% C.L.)

Single top production and colored singlet state

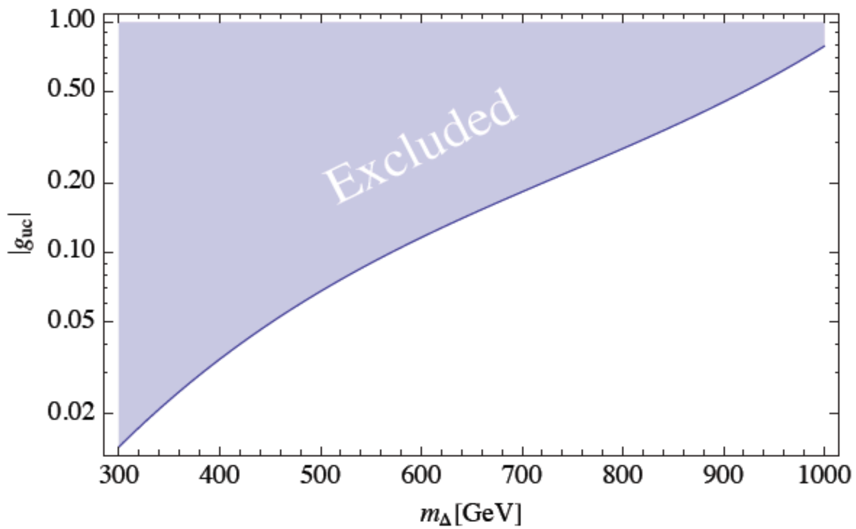


Partonic contribution to the single top production at the Tevatron from a u channel Δ_6 exchange. S-channel contribution can simply be obtained crossing.

The single top production is sensitive to the product $|g_6^{uc} g_6^{ut*}|$

Tevatron result: $\sigma_{1t} = 2.76^{+0.58}_{-0.47}$ pb

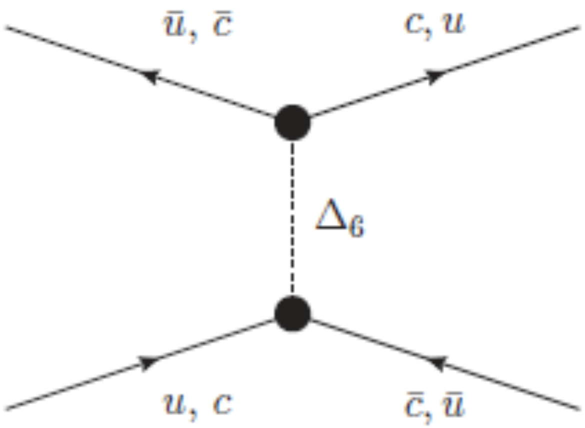
We require that $\sigma_{1t}^{(\Delta_6)} \leq 1\text{pb}$ at 95 % C.L>

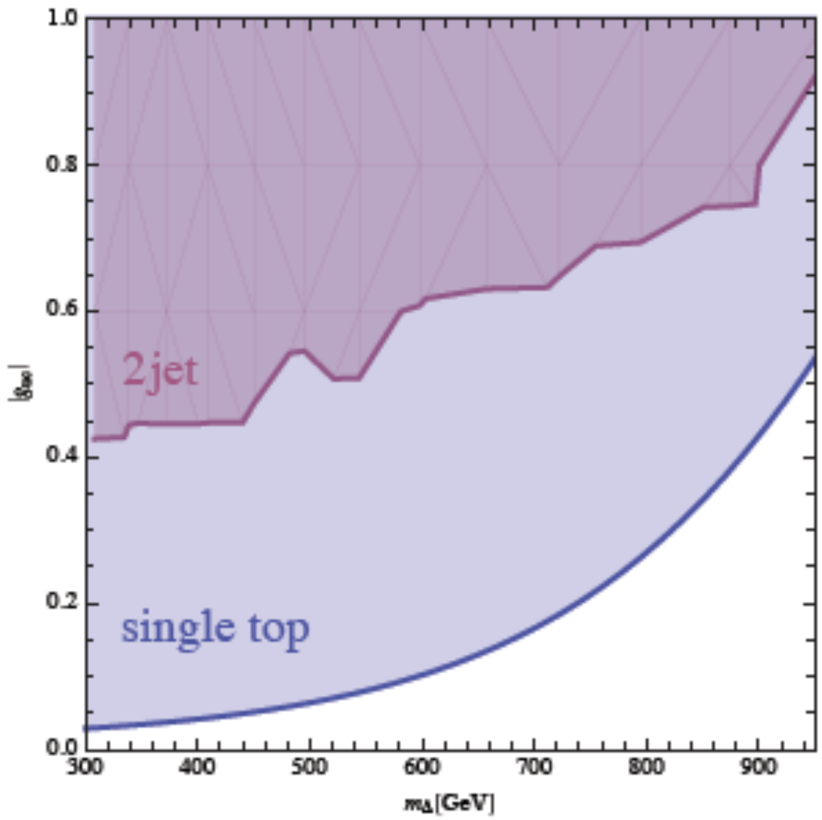


The coupling g_6^{uc} can be in principle constrained in the two di-jet events:

$$u\bar{u} \longrightarrow c\bar{c}$$
$$c\bar{c} \longrightarrow u\bar{u}$$

The rest of the processes can be obtained by crossing

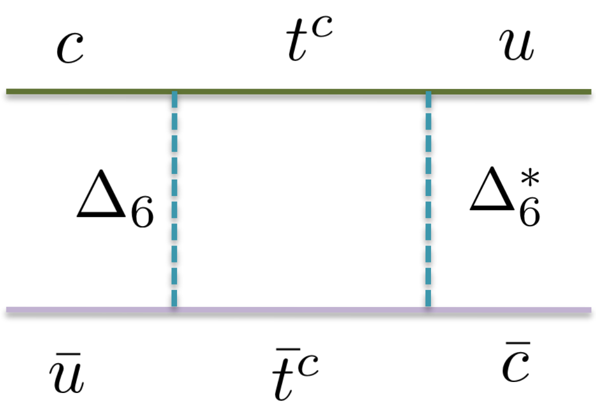




Bounds on g_6^{uc}

Colored scalars and charm meson processes

Charm quark processes with Δ_6 and Δ_1

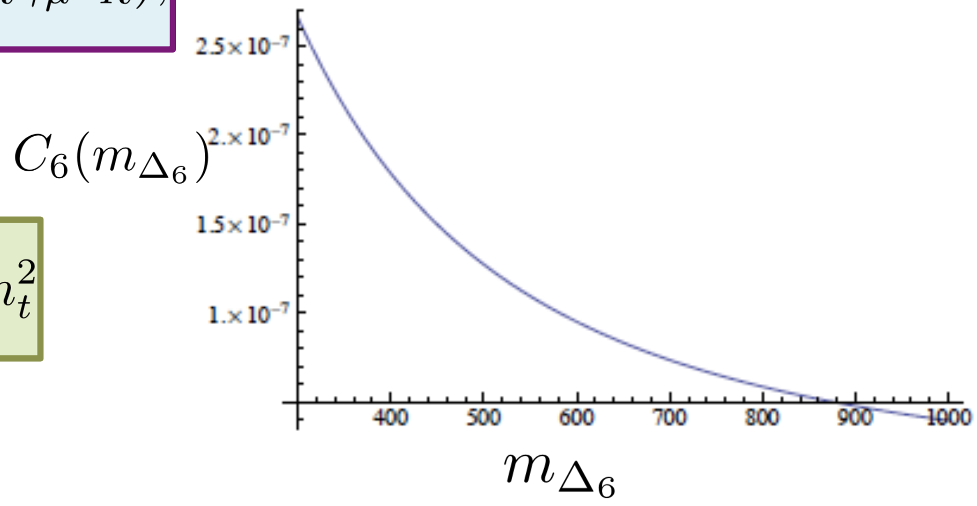


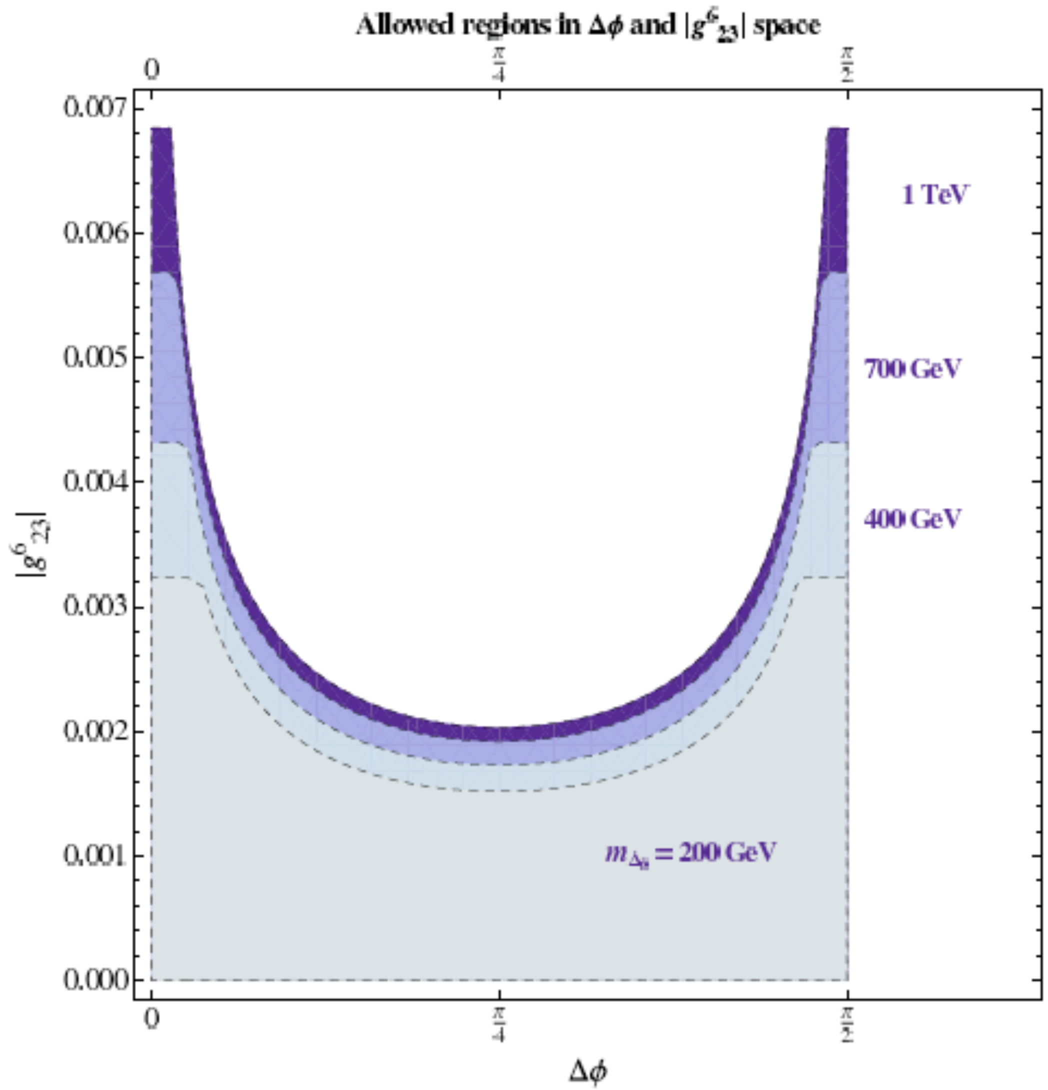
$$\mathcal{L}(\Delta_6) = g^6_{ij}\epsilon_{abc}\bar{u}^C_{ia}P_L u^C_{jb}\Delta_{6c}$$

$$\boxed{g^6_{ij} = 2\sqrt{2}[U_R^\dagger((Y_2)_{ij} - (Y_2)_{ji})U_R^*]}$$

$$\boxed{H^{\Delta C=2} = \underbrace{\frac{g^2_{13}(g^{6*}_{23})^2 h(x)}{32\pi^2 m_t^2}}_{C_6(m_{\Delta_6})}(\bar{u}_R\gamma^\mu c_R)(\bar{u}_R\gamma_\mu c_R),}$$

$$\boxed{h(x) = \frac{x^2 - 2x\ln x - 1}{(x-1)^3}, \qquad x = m_\Delta^2/m_t^2}$$





relative phase between
g^6_{13} and g^6_{23}

CP violating phase comes from the relative phase between (ut) and (ct) couplings

Bound on imaginary part of the Wilson coefficient is the dominant constraint, except for in the region close $\phi = 0 \text{ or } \pi/2$

$$m_{\Delta_6} < 1 \text{ TeV:}$$

$$|g_6^{23}| < 0.007$$

(regardless of phase)

Constraints on anti-symmetric Yukawa couplings

$$\mathcal{L} = (Y_1)_{ij} e_i^{cT} C d_{aj}^c \Delta_{6a}^* + \sqrt{2}[(Y_2)_{ij} - (Y_2)_{ji}] \epsilon_{abc} u_i^{aT} C u_{bj}^c \Delta_{6c}$$

$$g_{ij}^6 = 2\sqrt{2}[U_R^\dagger((Y_2)_{ij} - (Y_2)_{ji})U_R^*]$$

$$g_{ij}^6 = -g_{ji}^6$$

Matrix which makes transformation
from the weak to the mass basis

Results

Our constraints on Yukawa come from the up-quark phenomenology

for

$$m_{\Delta_6} = 400\,\mathrm{GeV}$$

$$\left\{ \begin{array}{c} |g_{13}^6| = 1.8 \\ |g_{23}^6| \leq 0.0043 \\ |g_{12}^6| \leq 0.03 \end{array} \right\}$$

Why does it matter?

$$
\begin{aligned}
V &= Y_{5^*}^{ij}\mathbf{10}_i^{\alpha\beta}\overline{\mathbf{5}}_{\alpha j}\mathbf{5}^*_{H\beta} + Y_5^{ij}\epsilon_{\alpha\beta\gamma\delta\epsilon}\mathbf{10}_i^{\alpha\beta}\mathbf{10}_j^{\gamma\delta}\mathbf{5}_H^{\epsilon} \\
&+ \underbrace{Y_{45^*}^{ij}}_{(Y_1)_{ij}}\mathbf{10}_i^{\alpha\beta}\overline{\mathbf{5}}_{\delta j}\mathbf{45}^{*\,\delta}_{H\alpha\beta} + \underbrace{Y_{45}^{ij}}_{(Y_2)_{ij}}\epsilon_{\alpha\beta\gamma\delta\epsilon}\mathbf{10}_i^{\alpha\beta}\mathbf{10}_j^{\zeta\gamma}\mathbf{45}_{H\zeta}^{\delta\epsilon},
\end{aligned}
$$

$$
\begin{aligned}
M_D &= (Y_{5*}v_5^* + 2Y_1 v_{45}^*)/\sqrt{2} \\
M_E &= (Y_{5*}v_5^* - 6Y_1 v_{45}^*)/\sqrt{2} \\
M_U &= [4(Y_5^T + Y_5)v_5 - 8(Y_2^T - Y_2)v_{45}]/\sqrt{2}
\end{aligned}
$$

Mass matrices at GUT scale
(weak basis)

$$\langle \mathbf{5}_H^5\rangle = v_5/\sqrt{2},\ \langle \mathbf{45}_{H1}^{15}\rangle = \langle \mathbf{45}_{H2}^{25}\rangle = \langle \mathbf{45}_{H3}^{35}\rangle = v_{45}/\sqrt{2}$$

$$|v_5|^2 + |v_{45}|^2 = v^2 \ \ (v = 247\ \text{GeV})$$

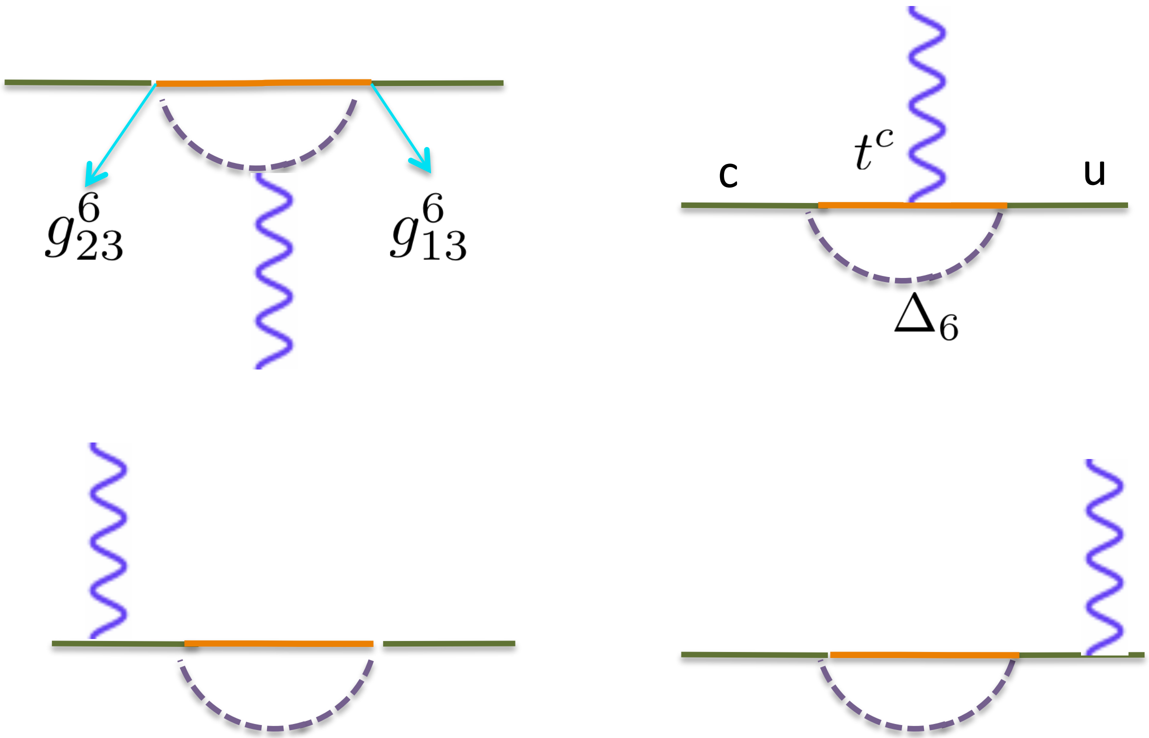
Goal: to learn full up-quark mass-matrix pattern, constrained by the experimental results in the up-quark sector!

Impact on the t and c FCNC rare decays

$$\boxed{c \longrightarrow u\gamma}$$

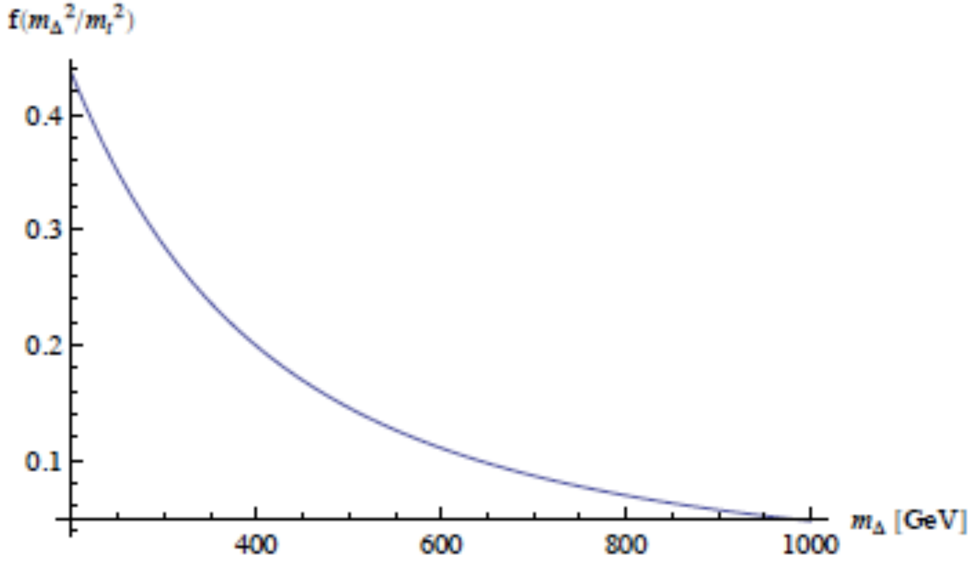
from charm meson oscillation bound on $\boxed{g^6_{23}}$

from top quark forward-backward asymmetry $\boxed{g^6_{13}}$



$$\boxed{\mathcal{M}_6(c \to u\gamma) = \frac{-2/3 e g_{13}^{6} g_{23}^{6*} \alpha_{em}}{32\pi^2 m_t^2} f(m_{\Delta_6}/m_t^2)\bar{u}\sigma_{\mu\nu}\epsilon_\mu^* q_\nu}$$

$$f(x) = \frac{1 - 6x + 3x^2 + 2x^3 - 6x^2 lnx}{(x-1)^4}$$

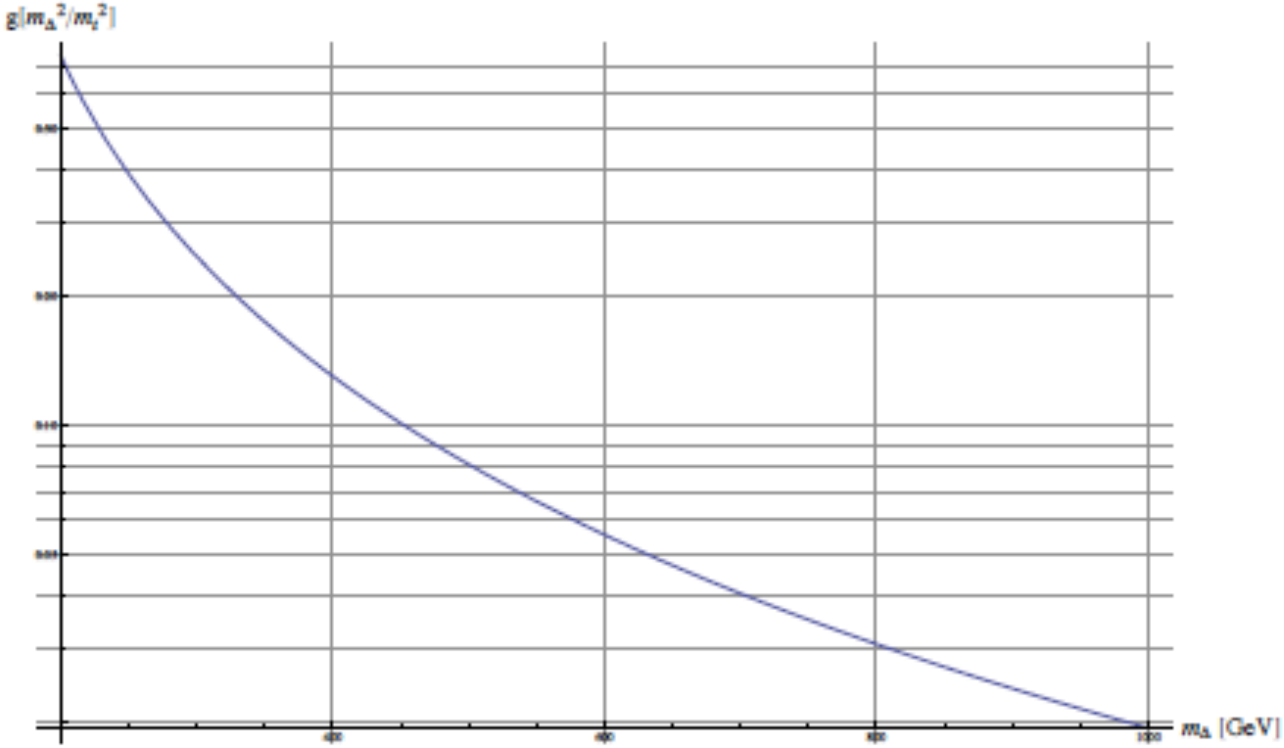


$$\boxed{BR(c \to u\gamma) = \underbrace{|g_{13}^{6} g_{23}^{6\,*}|^2 2.4 \times 10^{-6}}_{\leq 2 \times 10^{-11}}}$$

We looked also at the bound coming from $\boxed{B(D^+ \to \pi^+\mu^+\mu^-) < 3.9 \times 10^{-6}}$

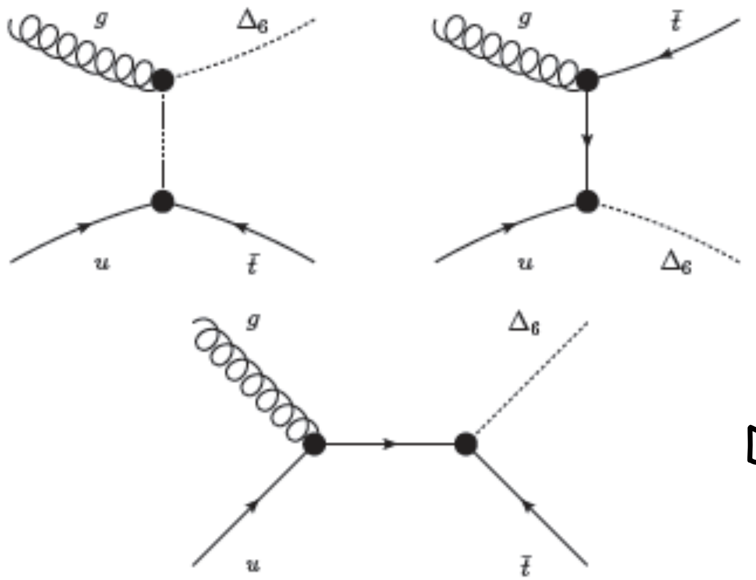
this is not so constraining $|g_{13}^{6} g_{23}^{6}| \leq \dfrac{90}{f(x)}$.

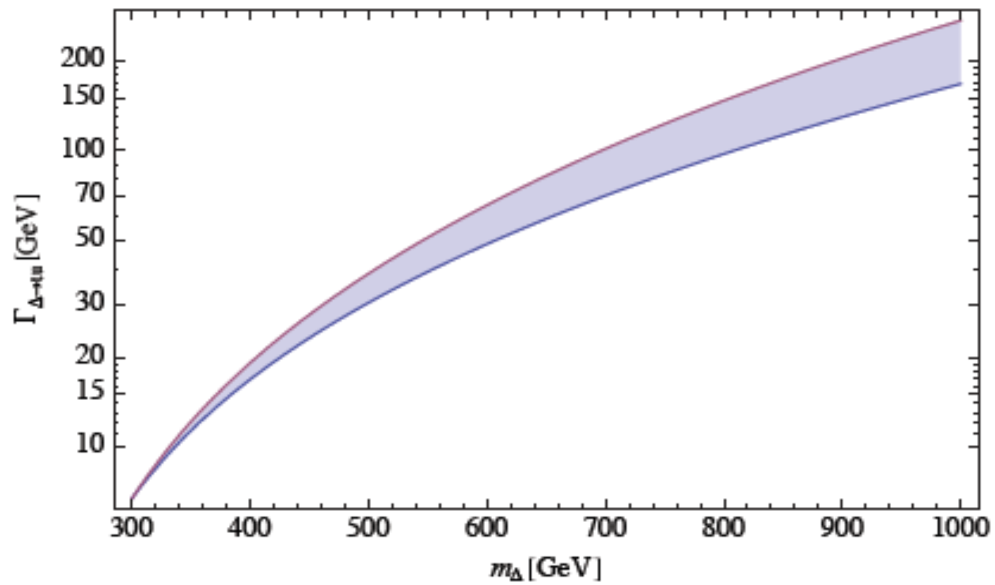
$$\boxed{t \longrightarrow c\gamma}$$



$$\boxed{BR(t \to u\gamma) = \underbrace{|g^{6}_{12} g^{6*}_{23}|^2 \times 10^{-7}}_{\leq 4 \times 10^{-11}}}$$

Search strategies at hadron colliders



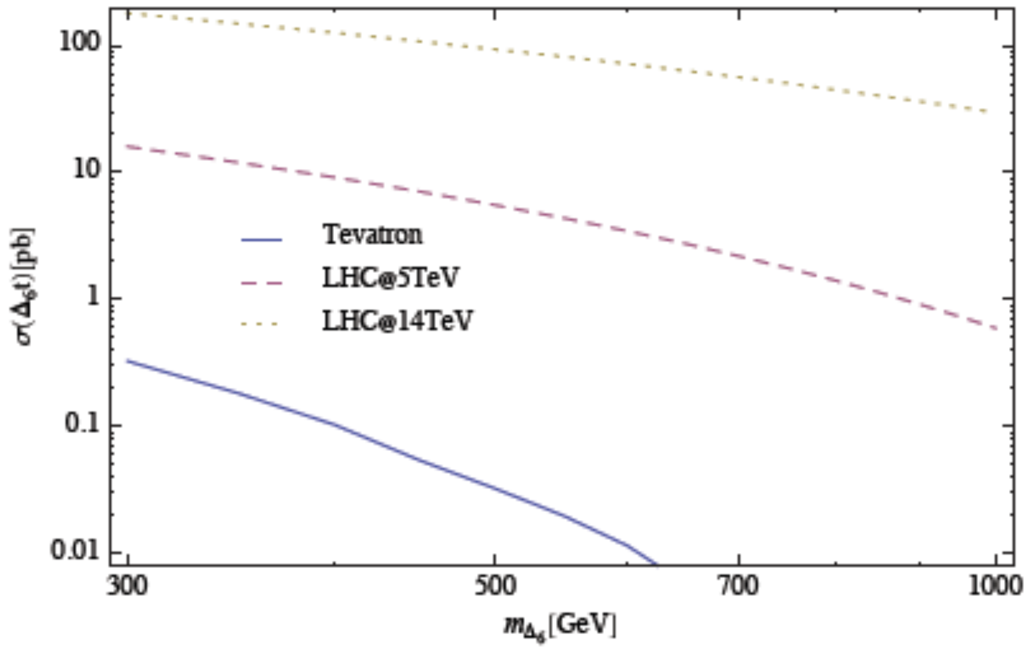


Dependence of the decay width on the Δ_6 mass .

$$\Gamma(\Delta_6 \to tu) = \frac{|g_6^{ut}|^2 \left(m_{\Delta_6}^2 - mt^2\right)^2}{16\pi m_{\Delta_6}^3}$$

$$\sigma_{t\bar{t}+j}^{\Delta_6} \approx (\sigma_{t\Delta_6^*} + \sigma_{\bar{t}\Delta_6}) \times Br(\Delta_6 \to tu)$$

Δ_6 can be produced at hadron colliders:



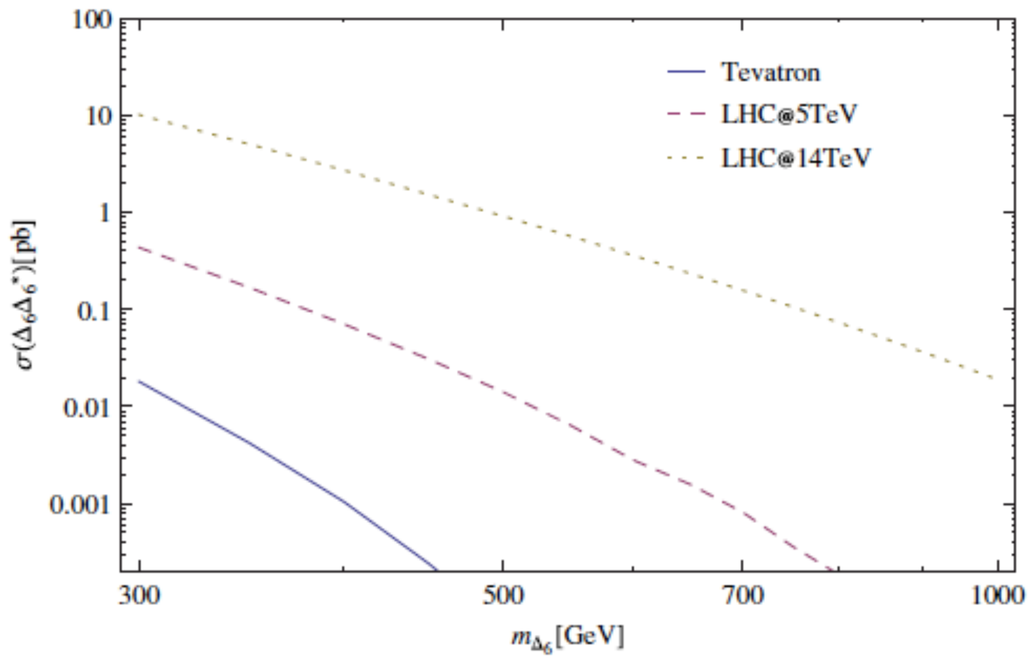
Hadronic production at LHC and Tevatron

Pair production

$$q\bar{q} \to \Delta_6 \Delta_6^*$$

$$gg \to \Delta_6 \Delta_6^*$$

Δ_6 would appear as a resonance in the invariant mass of a top and one hard jet.



Conclusions

- SU(5) GUT model including 45 enables unification with two relatively light colored scalars Δ_6, Δ_1 , which are within LHC reach;

- Moderate increase in the proton decay measurement will constrain presently allowed mass range for the Δ_6, Δ_1 ;

- Model offers a possibility to explain FB asymmetry in top pair production at Tevatron, without spoiling the SM prediction for the cross section;

- $D^0 - \bar{D}^0$ system might constrain Yukawa couplings;

- Constraints on Yukawa couplings coming from the FB asymmetry in the production $t\bar{t}$ and $D^0 - \bar{D}^0$ appear in the FCNC processes $t \to c\gamma$ and $c \to u\gamma$;

- Might help in understanding a pattern of Yukawa mass matrix for the u-quarks.

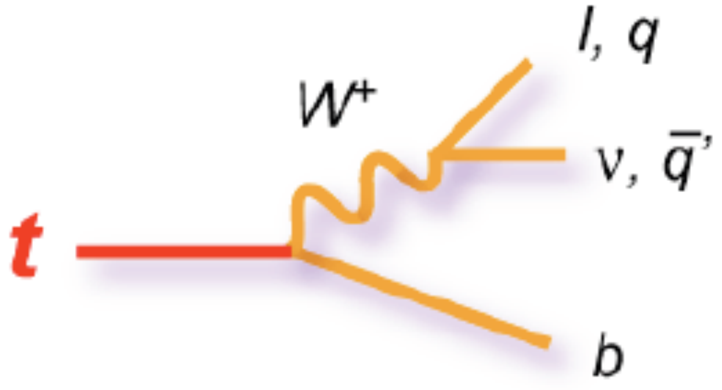
- The best strategy for the experimental search for the Δ_6 state would be to study the spectrum of the $t\bar{t}$ + jet production and search for resonances in the invariant mass of the light jet together with top or antitop.

Dominant decay modes:

$$t \to Wq$$

Important CKM matrix elements $V_{tb}, \quad V_{ts}, \quad V_{td}$

$$\frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$



$$\Gamma(t \to W^+ q) \approx 1.5 \text{ GeV} > \Lambda_{QCD} \sim 200 \text{ MeV}$$

Proton decay

Δ_6 can mix via the Higgs doublet that has the right diquark couplings to destabilize proton.

In our scenarios there is only one adjoint representation with

$$\mathbf{24} \equiv (\Sigma_8, \Sigma_3, \Sigma_{(3,2)}, \Sigma_{(\overline{3},2)}, \Sigma_{24})$$

$$(\mathbf{8},\mathbf{1},0) \oplus (\mathbf{1},\mathbf{3},0) \oplus \underbrace{(\mathbf{3},\mathbf{2},-5/6) \oplus (\overline{\mathbf{3}},\mathbf{2},5/6)} \oplus (\mathbf{1},\mathbf{1},0)$$

$\Sigma_{(3,2)}$ and $\Sigma_{(\overline{3},2)}$ always get "eaten" by X and Y gauge bosons and thus prohibited from mixing

Additional constraints: ρ_8 must be heavier than $10^6\,\mathrm{GeV}$ to accommodate Big Bang nucleosynthesis.

P. Fileviez Perez, 2007;

$$m_{\rho_8} = \hat{m} m_{\rho_3}, \qquad m_{\rho_{(3,2)}} = m_{\rho_{(3,2)}} = \frac{(1+\hat{m})}{2} m_{\rho_3}$$

measures mass splitting between ρ_8 and ρ_3

Study of parameter space

unification possible if $\boxed{10^{6.4} \leq \hat{m} \leq 10^{14.2}}$

and Δ_6 can be light $\boxed{300\,\mathrm{GeV} \leq m_{\Delta_6} \leq 1\,\mathrm{TeV}}$

If experimental limit for the proton decay is improved for one order of magnitude this allowed will be excluded!

$$\mathcal{H}_{\text{eff}}^{\Delta C=2} = \frac{1}{\Lambda_{\text{NP}}^2}\left(\sum_{i=1}^{5} z_i Q_i^{cu} + \sum_{i=1}^{3} \tilde{z}_i \tilde{Q}_i^{cu}\right),$$

L $\longleftrightarrow$ R

Gedalia et al.

$$Q_1^{cu} = \bar{u}_L^\alpha \gamma_\mu c_L^\alpha \bar{u}_L^\beta \gamma^\mu c_L^\beta, \qquad Q_2^{cu} = \bar{u}_R^\alpha c_L^\alpha \bar{u}_R^\beta c_L^\beta,$$
$$Q_3^{cu} = \bar{u}_R^\alpha c_L^\beta \bar{u}_R^\beta c_L^\alpha, \qquad Q_4^{cu} = \bar{u}_R^\alpha c_L^\alpha \bar{u}_L^\beta c_R^\beta,$$
$$Q_5^{cu} = \bar{u}_R^\alpha c_L^\beta \bar{u}_L^\beta c_R^\alpha,$$

In the absence of direct CP violation, using all experimental constraints:

$$|z_1| \lesssim 5.7 \times 10^{-7}\left(\frac{\Lambda_{\text{NP}}}{1\ \text{TeV}}\right)^2,$$
$$|z_2| \lesssim 1.6 \times 10^{-7}\left(\frac{\Lambda_{\text{NP}}}{1\ \text{TeV}}\right)^2,$$
$$|z_3| \lesssim 5.8 \times 10^{-7}\left(\frac{\Lambda_{\text{NP}}}{1\ \text{TeV}}\right)^2,$$
$$|z_4| \lesssim 5.6 \times 10^{-8}\left(\frac{\Lambda_{\text{NP}}}{1\ \text{TeV}}\right)^2,$$
$$|z_5| \lesssim 1.6 \times 10^{-7}\left(\frac{\Lambda_{\text{NP}}}{1\ \text{TeV}}\right)^2.$$

$$\text{Im}(z_1) \lesssim 1.1 \times 10^{-7}\left(\frac{\Lambda_{\text{NP}}}{1\ \text{TeV}}\right)^2,$$
$$\text{Im}(z_2) \lesssim 2.9 \times 10^{-8}\left(\frac{\Lambda_{\text{NP}}}{1\ \text{TeV}}\right)^2,$$
$$\text{Im}(z_3) \lesssim 1.1 \times 10^{-7}\left(\frac{\Lambda_{\text{NP}}}{1\ \text{TeV}}\right)^2,$$
$$\text{Im}(z_4) \lesssim 1.1 \times 10^{-8}\left(\frac{\Lambda_{\text{NP}}}{1\ \text{TeV}}\right)^2,$$
$$\text{Im}(z_5) \lesssim 3.0 \times 10^{-8}\left(\frac{\Lambda_{\text{NP}}}{1\ \text{TeV}}\right)^2.$$

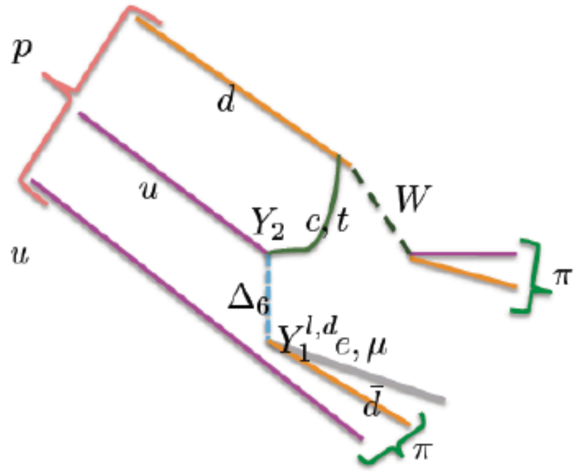
Proton decay?

Δ_6 — innocuous for proton decay at the tree level, but might mix via Higgs doublet with scalar that has right quantum numbers to destabilize proton.

In our scenarios there is only one adjoint representation with

$$\mathbf{24} \equiv (\Sigma_8, \Sigma_3, \underbrace{\Sigma_{(3,2)}, \Sigma_{(\overline{3},2)}}, \Sigma_{24})$$

always get "eaten" by X and Y gauge bosons and thus prohibited from mixing



$$\mathcal{A}(p \to 2\pi\ell^+, \pi^+\ell^+\ell'^-\nu) \sim Y_1^{\ell 1}(V_{cd}^* g_6^{12}/m_c^2 + V_{td}^* g_6^{13}/m_t^2)$$

has to be close to 0!

$$\boxed{\Delta_1 = (8, 2, 1/3)}$$

Manohar and Wise, 2006; Gersham and Wise, 2007; Burgess et al, 2009;
P.F. Perez and Wise, 2009;